

PHYSICAL REVIEW C **68**, 061901(R) (2003)**Strange Pentaquark Hadrons in Statistical Hadronization**

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(Dated: October 15, 2003, Published December 22, 2003)

We study, within the statistical hadronization model, the influence of narrow strangeness carrying baryon resonances (pentaquarks) on the understanding of particle production in relativistic heavy ion collisions. There is a great variation of expected yields as function of heavy ion collision energy due to rapidly evolving chemical conditions at particle chemical freeze-out. At relatively low collision energies, these new states lead to improvement of statistical hadronization fits.

PACS numbers: 24.10.Pa, 25.75.-q, 13.60.Rj, 12.38.Mh

Enhanced production of strange hadrons in relativistic heavy ion collisions is well established [1, 2]. The availability of a high abundance of strangeness favors production of strange hadron resonances, a topic of current intense experimental interest in the field of relativistic heavy ion collisions [3, 4, 5, 6, 7, 8, 9]. The discovery by the NA49 collaboration [10] of a new $\Xi^{--}(1862)$ $I = 3/2$ narrow $\Gamma < 5$ MeV resonance in their pp background, rather than in the AA foreground data at projectile energy 158 GeV ($\sqrt{s_{NN}} = 17.2$ GeV) poses the question in which conditions one should look in heavy ion collisions for such new resonances.

This newly discovered hadron resonance has, given the mass and charge, an exceedingly narrow width. This feature is common with $\Theta^+(1540)$, another recently reported resonance [11, 12, 13, 14], which decays into the channel with quark content $uudd\bar{s}$ and $I = 0$. This is believed to be the predicted [15], lowest mass, pentaquark state [16]. The $\Xi^*(1862)$ can be interpreted as its most massive isospin quartet member $ssdd\bar{u}$, $ssud\bar{u}$, $ssud\bar{d}$, $ssuud\bar{d}$ with electrical charge varying, respectively, from -2 to $+1$, in units of $|e|$.

Appearance of these new resonances can have many consequences in the field of heavy ion collisions. We at first explore how the introduction into the family of hadronic particles of these two new resonances, $\Theta^+(1540)$ and $\Xi^*(1862)$, influence the results of statistical hadronization fit to relativistic heavy ion hadron production experimental results. We use the same data set as has been employed in Ref [2, 17, 18] and obtain predictions of how the relative abundances of these new resonant states vary as function of the heavy ion collision energy.

Importantly, only the two already identified states with $I = 0$, and $I = 3/2$ of the anti decuplet, which also includes the $I = 1/2$, and $I = 1$ states are of relevance in the study of the statistical hadronization fits. Thus, in

our analysis, we do not depend on the unknown masses of $I = 1/2$, and $I = 1$ states. However, the interpretation of the newly discovered narrow states as pentaquarks enters our considerations decisively. The pentaquark valance quark content enters the assigned chemical fugacities and phase space occupancies. The yield is proportional to the presumed spin degeneracy of the new states, taken to be two for a spin $1/2$ anti decuplet.

In our approach [2, 17, 18], as in other recent work [19], the chemical equilibrium and non-equilibrium is considered. Accordingly, we allow quark pair phase space occupancies, for light quarks $\gamma_q \neq 1$, and/or strange quarks $\gamma_s \neq 1$ [20]. Since we study at SPS the total particle multiplicities, and at RHIC the central yields which can be considered produced by rapidity-localized fireballs of matter, we require in our fits balance in the strange and anti-strange quark content [21].

There are two independent fit parameters when we assume complete chemical equilibrium, the chemical freeze-out temperature T and the light quark fugacity $\lambda_q = \sqrt{\lambda_u \lambda_d} = e^{\mu_b/(3T)}$. The baryochemical potential μ_b is the physical parameter controlling baryon density. Strangeness conservation fixes the strange quark fugacity λ_s (equivalently, strangeness chemical potential, for more details see, e.g., [2]). Adding the possibility that the number of strange quark pairs is not in chemical equilibrium, $\gamma_s \neq 1$, we have 3 parameters, and allowing also that light quark pair number is not in chemical equilibrium, we have 4 parameters. These three alternatives will be coded as open triangles, open squares and filled squares, respectively, in all results we present graphically.

We find that the new resonance $\Theta^+(1540)$ influences significantly the statistical hadronization fit to particle production at the lowest SPS energies. In a baryon rich environment the introduction into the fit of $\Theta^+(1540)$, a $b = 1$ baryon with ‘wrong’ strangeness influences the strangeness balance condition, and thus indirectly the

TABLE I: The chemical freeze-out statistical parameters found for nonequilibrium (left) and semi equilibrium (right) fits to SPS results. We show $\sqrt{s_{NN}}$, the temperature T , light quark fugacity λ_q , strange quark fugacity λ_s , the quark occupancy parameters γ_q and γ_s/γ_q . Bottom line presents the statistical significance of the fit. The star (*) indicates for λ_s that it is a value resulting from strangeness conservation constraint. For γ_q that there is an upper limit to which the value converged, $\gamma_q^2 < e^{m_\pi/T}$ (on left), or that the value of $\gamma_q = 1$ is set (on right).

$\sqrt{s_{NN}}$ [GeV]	17.2	12.3	8.75	17.2	12.3	8.75
T [MeV]	135 ± 3	135 ± 3	133 ± 2	157 ± 4	156 ± 4	154 ± 3
λ_q	1.69(5)	1.98(6)	2.56(6)	1.74(5)	2.03(7)	2.69(8)
λ_s	1.23*	1.27*	1.31*	1.20*	1.24*	1.24*
γ_q	1.68*	1.68*	1.69*	1*	1*	1*
γ_s/γ_q	0.91(6)	0.83(4)	0.85(6)	0.66(4)	0.60(4)	0.67(5)
χ^2/dof	11.4/6	4.3/2	2.3/4	23/7	8.9/3	4.0/5

TABLE II: The chemical freeze-out statistical parameters found for nonequilibrium (left) and semi equilibrium (right) fits to RHIC results. We show $\sqrt{s_{NN}}$, the temperature T , light quark fugacity λ_q , strange quark fugacity λ_s , the quark occupancy parameters γ_q and γ_s/γ_q . Bottom line presents the statistical significance of the fit. The star (*) indicates for λ_s that it is a value resulting from strangeness conservation constraint. For γ_q that there is an upper limit to which the value converged, $\gamma_q^2 < e^{m_\pi/T}$ (on left), or that the value of $\gamma_q = 1$ is set (on right).

$\sqrt{s_{NN}}$ [GeV]	200	130	200	130
T [MeV]	142 ± 5	143 ± 3	159 ± 6	159 ± 2
λ_q	1.051(9)	1.069(8)	1.052(9)	1.067(8)
λ_s	1.018*	1.023*	1.018*	1.023*
γ_q	1.62*	1.63*	1*	1*
γ_s/γ_q	1.23(12)	1.32(5)	1.013(6)	1.13(4)
χ^2/dof	2.9/6	16.9/20	4.6/7	32.7/21

individual yields of all strange hadrons. This leads to a reduction in the statistical fit error for our hadronization study of the 40A GeV Pb–Pb reactions where we see a significant change in the relative yield of kaons and Λ . We also find changes in the details of the statistical fit parameters. In comparison to [17], aside of the introduction of the new resonances, we also have harmonized our hadron decay table with those used by the Kraków group [22]. The improvement of the particle yield fit is both, a theoretical confirmation of the validity of the statistical hadronization model of particle production, and its applicability at low SPS energies.

We show how the fit error evolves in figure 1, which is also presented in the bottom lines of tables I and II along with the number of data points and resulting degrees of freedom. Considering the small number of degrees of freedom at SPS, we need $\chi^2/\text{dof} < 1$ to have good significance of the fit. The errors seen in figure 1 are, for the chemical nonequilibrium case (filled squares), sufficiently small to allow us to conclude that the introduction of

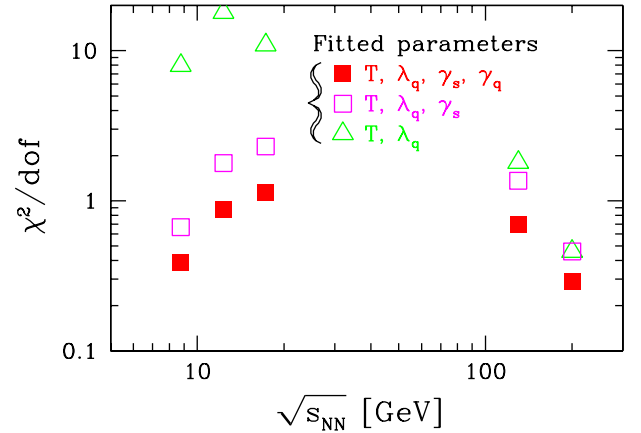


FIG. 1: (Color online) χ^2/dof for statistical hadronization fits at SPS and RHIC: results are shown for 40, 80, 158A GeV Pb on stationary Pb target collisions and at RHIC for 65+65 and 100+100A GeV Au–Au head on interactions.

$\Theta^+(1540)$ assures that the statistical hadronization works well down to the lowest SPS energies. To compare with earlier results on χ^2/dof , obtained prior to the discovery of these new resonances, see Ref. [17], figure 16.

An interesting point, seen in figure 1, is that the chemical equilibrium fit $\gamma_s = 1, \gamma_q = 1$ is rendered unacceptable at all SPS energies in presence of the new resonances. The semi-equilibrium fit, which allows a varying strangeness saturation, but assumes light quark equilibrium is generally resulting in twice as large χ^2 compared to the full non-equilibrium approach. In a study of χ^2 profile as function of γ_q we find a clear and strong minimum for $\gamma_q \rightarrow \gamma_q^{\text{max}} \equiv e^{-m_\pi/(2T)}$. Acquisition by the fit of this limiting value implies that there is no fitting error in the γ_q presented below.

The chemical freeze-out parameters of the fits considered play a very important role in predicting the (relative) yield of hadronic particles, and this dependence is even stronger for many pentaquark states, due to their

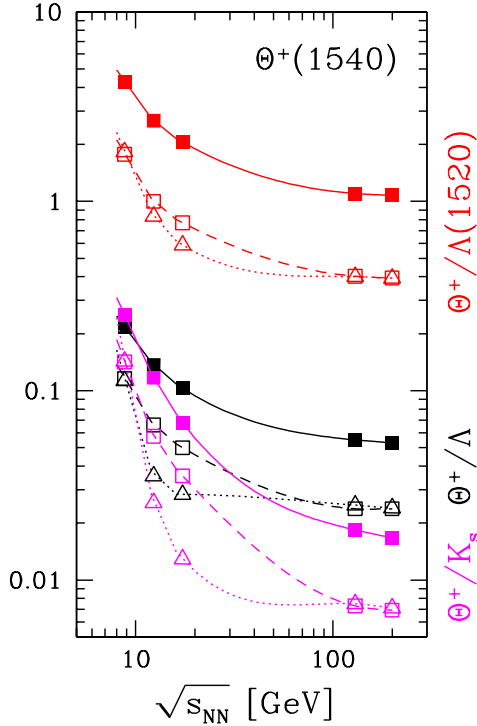


FIG. 2: (Color online) Yield of $\Theta^+(1540)$ in relativistic heavy ion collisions, based on statistical hadronization fit to hadronization parameters at SPS and RHIC 40, 80, 158 A GeV Pb on stationary Pb target collisions and at RHIC for 65+65 and 100+100 A GeV Au-Au head on interactions. Relative yields with K_s , Λ , and $\Lambda(1520)$ are shown from bottom to top.

unusual quantum numbers. These fit parameters for RHIC are shown in table II, and for SPS in table I along with the freeze-out temperature. We note that for the full chemical non-equilibrium, the freeze-out temperature is found to be smaller than for semi-equilibrium case. This reduction is over-compensated in pentaquark yields by the significantly increased value of γ_q .

We now consider the relative yields of the new resonances in figures 2 and 3. These yields vary strongly with collision energy for the case of $\Theta^+(1540)$ in figure 2, but are rather constant in figure 3. Certainly our result differs greatly from expectations arising from an earlier study of the statistical model production of the $\Theta^+(1540)$ resonance [23] where the decisive variation of the particle yield with chemical potentials was not explored. Moreover, the hadron yields, presented in [23], did not include the contributions from decay of short lived hadron resonances. We checked that the relative particle yields shown in [23] for zero chemical potentials and varying temperature are mathematically correct, also as a cross check of our program.

In figure 2, we show (from top to bottom) the relative yields $\Theta^+(1540)/\Lambda(1520)$, $\Theta^+(1540)/\Lambda$, $\Theta^+(1540)/K_s$ for chemical nonequilibrium (solid lines), semi-equilibrium ($\gamma_q = 1$, dashed lines) and chemical equilibrium (dotted lines). The yields of Λ used here

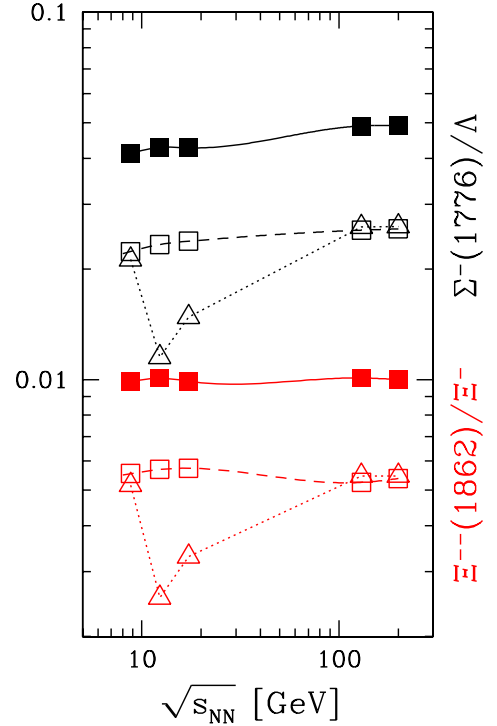


FIG. 3: (Color online) Relative yields $\Xi^-(1862)/\Xi^-$ and $\Xi^-(1786)/\Lambda$ are shown from bottom to top, see figure 2 for further details.

include 50% weak interaction cascade from Ξ .

The reason that the chemical nonequilibrium is leading to greater than equilibrium yields is that the lower hadronization temperature is overcompensated by the chemical factors, e.g., $\Theta^+(1540)/\Lambda(1520) \simeq 1/2 \gamma_q^2 (\lambda_q/\lambda_s)^2$ ignoring the small mass difference. The factor 1/2 is due to the difference in spin degeneracy. The actually observed yield ratio $\Theta^+(1540)/\Lambda(1520)$ could be still greater since $\Lambda(1520)$ is seen at 50% of the expected statistical hadronization yield in heavy ion collisions. In figure 2, we also recognize that the reason that there is such a significant impact at low SPS energies of $\Theta^+(1540)$ is that it is produced at the level of +10–20% of Λ in fits at 40 A GeV. This is due to the large prevailing baryochemical density. Clearly, this is the environment in which one would want to study the properties of this new resonance in more detail. However, at all energies considered, we find that $\Theta^+(1540)$ is more abundant compared to $\Lambda(1520)$ and thus this new resonance could become an important probe of the hadronization dynamics.

The observation of the pattern of relative yield of $\Theta^+(1540)$, seen in figure 2, would firmly confirm the 4-quark, one anti quark content of this state. Namely, were for example the $\Theta^+(1540)$ another tri-quark baryon state, the yield ratio with (strange) baryons would be quite flat as function of collision energy. We further note that the absolute magnitude of the relative yield, seen in figure 2, will be of help in establishing the degree of chemical equilibration.

In figure 3, we show at the bottom the expected rel-

ative yield of the $\Xi^{--}(1862)[ssdd\bar{u}]$ relative to $\Xi^{-}[ssd]$. The $\Xi^{*}(1862)$ adds at the percentile level to the yield of observed Ξ and thus it is less influential in the statistical hadronization approach. The absence of variation of the relative yield with collision energy is due to cancellation of chemical factors. This relatively small relative yield at all collision energies here considered shows that indeed the pp environment, where it has been identified by the NA49 collaboration, is most suitable. The dotted lines, in figure 3, are visibly breaking the trend in some of the results, indicating that the large χ^2 chemical equilibrium fit generates unreliable statistical model parameters.

We also show, in figure 3 on the top, the yield of the pentaquark state $\Sigma(1776)[sddu\bar{u}]$ which for purpose of this study is assumed at the mass indicated. Again due to cancellation of key chemical factors in ratios shown in figure 3, both being proportional to $\gamma_q^2 \lambda_d / \lambda_u$, the ratio is flat (except for the failed fit chemical equilibrium results). Considering that $\lambda_d \simeq \lambda_u$ and $\gamma_q \simeq 1.6$, the magnitude

of relative yields seen in figure 3 is primarily due to the hadron mass, and degeneracy.

We have shown that inclusion of the pentaquark states in the study of particle production in heavy ion collisions improves the quality of our fits to experimental data. We find that $\Theta^{+}(1540)$ state influences the low energy SPS particle yield fit results. It can be expected that it will be detectable, in particular at low heavy ion collision energies, and thus should become a new probe of hadronization dynamics. The other pentaquark states will be hard to observe in heavy ion collisions.

Work supported in part by a grant from the U.S. Department of Energy, DE-FG03-95ER40937. LPTHE, Univ. Paris 6 et 7 is: Unité mixte de Recherche du CNRS, UMR7589.

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